

CHANGE OF MIT BAG CONSTANT IN NUCLEAR MEDIUM AND IMPLICATION FOR THE EMC EFFECT

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Abstract

The modified quark-meson coupling model, which features a density dependent bag constant and bag radius in nuclear matter, is checked against the EMC effect within the framework of dynamical rescaling. Our emphasis is on the change in the average bag radius in nuclei, as evaluated in a local density approximation, and its implication for the rescaling parameter. We find that when the bag constant in nuclear matter is significantly reduced from its free-space value, the resulting rescaling parameter is in good agreement with that required to explain the observed depletion of the structure functions in the medium Bjorken x region. Such a large reduction of the bag constant also implies large and canceling Lorentz scalar and vector potentials for the nucleon in nuclear matter which are comparable to those suggested by the relativistic nuclear phenomenology and finite-density QCD sum rules.

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I. INTRODUCTION

While most nuclear models treat nucleons and mesons as the relevant degrees of freedom for describing low- and medium-energy nuclear physics, nuclear effects on nucleon structure functions, the EMC effect [1], reveal the distortion of internal structure of the nucleon by the nuclear medium [2]. To study this distortion, it is desirable to build models that incorporate the fundamental building blocks of the nucleon, quark and gluon degrees of freedom, yet respect the established theories based on hadronic degrees of freedom. Since the underlying theory of strong interactions, quantum chromodynamics (QCD), is intractable at the nuclear physics energy scales, such models are necessarily quite crude.

The quark-meson coupling (QMC) model, proposed by Guichon [3], provides a simple and attractive framework to incorporate the quark structure of the nucleon in the study of nuclear phenomena. In this model, nuclear matter consists of non-overlapping MIT bags interacting through the self-consistent exchange of mesons in the mean-field approximation, and the mesons are coupled directly to the quarks inside the nucleon bags. This simple QMC model has been refined by including nucleon Fermi motion and the center-of-mass corrections to the bag energy [4] and applied to variety of nuclear physics problems [3–9]. (There have been several works that also discuss the quark effects in nuclei, based on other effective models for the nucleon [10]).

Recently, the present authors have pointed out that the assumption of fixing the MIT bag constant at its free-space value, adopted in the simple QMC model, is questionable and have modified the QMC model by allowing the bag constant to depend on the local density or sigma field. [11–13]. This modification can lead to the recovery of relativistic nuclear phenomenology, in particular the large canceling isoscalar Lorentz scalar and vector potentials and hence the strong spin-orbit force for the nucleon in nuclear matter. It is known that such features are essential to the success of the relativistic nuclear phenomenology [14]. However, comparison to relativistic nuclear phenomenology [14] and finite-density QCD sum rules [15] suggests a large reduction of the bag constant in nuclear matter.

In this paper, we examine the implications for the EMC effect of having the bag constant decrease in the nuclear medium. We shall be concerned only with the so-called EMC effect region, i.e., the Bjorken x region of $0.2 < x < 0.7$. The most important feature in this region is that the structure function of a bound nucleon is depleted with respect to that of a free nucleon and this depletion is nucleus dependent [2]. Since the structure functions in the medium x regime are dominated by the valence quark distributions, it may be reasonable to investigate the EMC effect in a simple valence-quark picture like the QMC model. (For smaller x , shadowing and antishadowing play a dominant role, and for larger x , Fermi motion of the nucleon takes over [2].)

Among many proposed theoretical explanations of the EMC effect is the dynamical rescaling [16–20]. (Reviews of various proposed mechanisms can be found in Ref. [2]). This approach relies on having the effective confinement size of quarks and gluons in a nucleus greater than that in a free nucleon [21]. Such a change in confinement scale implies a reduction in the momentum carried by the valence quarks and hence predicts, in the framework of perturbative QCD, that the structure function (in the EMC effect region) of a bound nucleon in nuclei can be related to that of a free nucleon by rescaling (in Q^2). The crucial input is the rescaling parameter, $\xi_A(Q^2)$ [Eq. (3.2)], which is determined by the

extent to which the confinement size changes from a free nucleon to a bound nucleon. This change was estimated in Refs. [16–18] by modeling the overlap of two nucleons, and it was found, for example, that the data can be explained if the confinement size in iron is $\sim 15\%$ larger than in an isolated nucleon. (The connections between the change of confinement scale and the EMC effect have also been discussed in Refs. [22–26]).

Decreasing the MIT bag constant in the nuclear medium, as implemented in the modified QMC model, implies a decrease of the bag pressure in nuclear environment. This leads to an increase of the bag radius in nuclei relative to its free-space value. Thus, the prediction of a change in the effective quark confinement size emerges naturally in the modified QMC model. This change yields a prediction for the rescaling parameter, which, in turn, gives rise to predictions for the EMC effect in the framework of dynamical rescaling.

We use a local density approximation to evaluate the average bag radius in a nucleus. This radius is then used to determine the rescaling parameter. We find that when the bag constant is significantly reduced in nuclear matter, e.g. $B/B_0 \sim 35 - 40\%$ at the nuclear matter saturation density, the predictions for the rescaling parameter are in good agreement with those required to explain the depletion of the structure function observed in a range of nuclei. Such a large reduction of the bag constant, as shown in previous works [11,12], also implies large and canceling Lorentz scalar and vector potentials for the nucleon in nuclear matter which are comparable to those suggested by the relativistic nuclear phenomenology and finite-density QCD sum rules. This indicates that the reduction of bag constant and hence the increase of confinement size in nuclei may play important role in low- and medium-energy nuclear physics and the modified QMC model provides a useful framework to accommodate both the change of confinement size and the quark structure of the nucleon in describing nuclear phenomena.

The nuclear structure functions have been studied by Thomas and collaborators [7] within the simple QMC model. (Similar study based on a soliton model for the in-medium nucleon was carried out in Ref. [27].) The technique assumed in these works is the same as the one used in calculating structure functions of a free nucleon from the MIT bag model [28]. We note that the resolution scale has been fixed at its value for free nucleon in these works. This is reasonable in the simple QMC model as the bag radius in nuclear matter only changes slightly compared to its free-space value. However, in the modified QMC model, the in-medium bag radius can be significantly altered and the approach used in Ref. [7] cannot be adopted directly. Our aim here is to simply study the implications of the change of confinement size in nuclei with respect to its free-space value for the EMC effect.

This paper is organized as follows: In Section II we sketch the modified QMC model for nuclear matter and evaluate the average bag radius in finite nuclei by using a local density approximation. In Section III we calculate the rescaling parameter from the change of the average bag radius relative to the bag radius of a free nucleon and discuss its implications for the EMC effect in the framework of dynamical rescaling. Further discussions are given in Section IV. Section V is a summary.

II. THE MODIFIED QMC MODEL AND BAG RADIUS IN NUCLEI

In this section, we first give a brief introduction to the modified quark-meson coupling model and then evaluate the average bag radius in nuclei by using a local density approximation. In the modified quark-meson coupling model the bag constant decreases and the nucleon bag swells when the nucleon is imbedded in the nuclear medium. The reader is referred to Refs. [11–13] for further details and motivations for introducing the medium modification of the bag constant.

A. The modified quark-meson coupling model

The QMC model depicts the nucleon in nuclear medium as a static spherical MIT bag in which quarks interact with the scalar and vector fields, $\bar{\sigma}$ and $\bar{\omega}$ [3]. These fields are treated as classical fields in the mean field approximation. The up and down quark fields, $\psi_q(t, \mathbf{r})$, inside the nucleon bag then satisfies the equation of motion:

$$\left[i \not{\partial} - (m_q^0 - g_\sigma^q \bar{\sigma}) - g_\omega^q \bar{\omega} \gamma^0 \right] \psi_q(t, \mathbf{r}) = 0 , \quad (2.1)$$

where m_q^0 is the current quark mass, and g_σ^q and g_ω^q denote the quark-meson coupling constants. For simplicity we will neglect isospin breaking and take $m_q^0 = (m_u^0 + m_d^0)/2 = 0$ hereafter. Inclusion of small current quark masses only yields numerically small refinements.

The energy of a static bag consisting of three ground state quarks can be expressed as

$$E_{\text{bag}} = 3 \frac{\Omega_q}{R} - \frac{Z}{R} + \frac{4}{3} \pi R^3 B , \quad (2.2)$$

where $\Omega_q \equiv \sqrt{y^2 + (R m_q^*)^2}$, $m_q^* = m_q^0 - g_\sigma^q \bar{\sigma}$, R is the bag radius, Z is a parameter which accounts for zero-point motion and B is the bag constant. The y value is determined by the boundary condition at the bag surface, $j_0(y) = \beta_q j_1(y)$, with $\beta_q = [(\Omega_q - R m_q^*)/(\Omega_q + R m_q^*)]^{1/2}$. In the discussions to follow, we use R_0 , B_0 and Z_0 to denote the corresponding bag parameters for the free nucleon. After the corrections of spurious center-of-mass motion in the bag, the effective mass of a nucleon bag at rest is taken to be [4,5]

$$M_N^* = \sqrt{E_{\text{bag}}^2 - \langle p_{\text{cm}}^2 \rangle} , \quad (2.3)$$

where $\langle p_{\text{cm}}^2 \rangle = \sum_q \langle p_q^2 \rangle$ and $\langle p_q^2 \rangle$ is the expectation value of the quark momentum squared, $(y/R)^2$.

The equilibrium condition for the bag is obtained by minimizing the effective mass M_N^* with respect to the bag radius

$$\frac{\partial M_N^*}{\partial R} = 0 . \quad (2.4)$$

In free space, one may fix M_N at its experimental value 939 MeV and use the equilibrium condition to determine the bag parameters. For several choices of bag radius, $R_0 = 0.6, 0.8, 1.0$ fm, the results for $B_0^{1/4}$ and Z_0 are 188.1, 157.5, 136.3 MeV and 2.030, 1.628, 1.153, respectively. Finally, the scalar mean field is determined by the thermodynamic condition

$$\left(\frac{\partial E_{\text{tot}}}{\partial \bar{\sigma}}\right)_{R, \rho_N} = 0. \quad (2.5)$$

The simple QMC model assumes that both Z and B are independent of density [3–5]. Such an assumption is questionable [11–13]. We have proposed two models for the modification of the bag constant.¹ The direct coupling model [12] (model-I) invokes a direct coupling of the bag constant to the scalar meson field

$$\frac{B}{B_0} = \left[1 - g_\sigma^B \frac{4}{\delta} \frac{\bar{\sigma}}{M_N}\right]^\delta, \quad (2.6)$$

where g_σ^B and δ are real positive parameters. In the limit of $\delta \rightarrow \infty$, Eq. (2.6) reduces to an exponential form, $B/B_0 = e^{-4g_\sigma^B \bar{\sigma}/M_N}$, with a single parameter g_σ^B . The scaling model [11,12] (model-II) relates the in-medium bag constant directly to the in-medium nucleon mass M_N^*

$$\frac{B}{B_0} = \left[\frac{M_N^*}{M_N}\right]^\kappa, \quad (2.7)$$

where κ is a real positive parameter.

One notices that both Eqs. (2.6) and (2.7) give rise to a reduction of the bag constant in nuclear medium relative to its free-space value. While the scaling model is characterized by a single free parameter κ , it leads to a complicated and implicit relation between the bag constant and the scalar mean field. On the other hand, the direct coupling model features a straightforward coupling between the bag constant and the scalar mean field, which, however, introduces two free parameters, g_σ^B and δ . Various couplings and other parameters can be adjusted to reproduce the nuclear matter binding energy (-16 MeV) at the saturation density ($\rho_N^0 = 0.17 \text{ fm}^{-3}$). The resulting coupling constants and nuclear matter results have been given in Refs. [11,12].

Here we are interested in the modification of the bag radius in nuclear medium. In the usual QMC model, the bag radius decreases slightly ($\sim 1\%$) and the quark root-mean-square (RMS) radius increases slightly ($\sim 1\%$) in saturated nuclear matter with respect to their free-space values [3,5]. When the bag constant drops relative to its free-space value, the bag pressure decreases and hence the bag radius increases in the medium. It has been found in Refs. [12,13] that if the reduction of the bag constant is significant (e.g. $B/B_0 \sim 35 - 40\%$), the bag radius in saturated nuclear matter is $25 - 30\%$ larger than its free-space value. This result is essentially determined by the value of B/B_0 at ρ_N^0 and largely insensitive to the model used for the in-medium bag constant. (The quark RMS radius also increases with density, with essentially the same rate as for the bag radius.) As an example, we have plotted in Fig. 1 the resulting bag radius as a function of ρ_N , with model-I, Eq. (2.6), for the in-medium bag constant. The corresponding bag constant is shown in Fig. 2. The results from model-II, Eq. (2.7), can be found in Ref. [11].

¹In principle, the parameter Z may also be modified in the nuclear medium. However, it is unclear how Z changes with the density. Here we assume that the medium modification of Z is small at

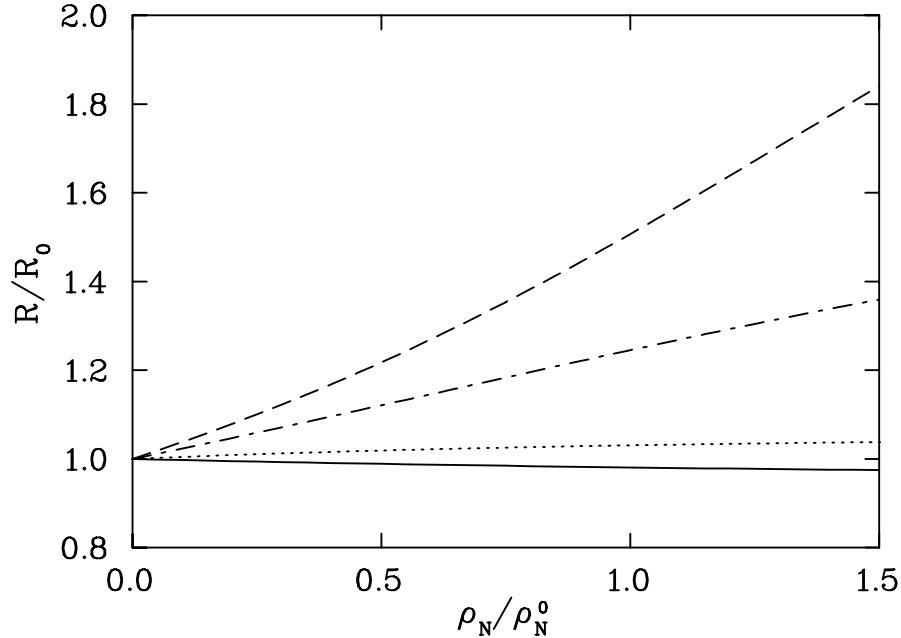


FIG. 1. Result for the ratio R/R_0 as a function of the medium density, with $\delta = 4$ and $R_0 = 0.6$ fm. Here model-I Eq. (2.6) is used for the in-medium bag constant. The couplings g_σ^B and g_σ^q are adjusted to fit the nuclear matter binding energy and the other parameters are the same as used in Ref. [12]. The four curves correspond to $g_\sigma^q = 1.0$ (long-dashed), 2.0 (dot-dashed), 4.0 (dotted), and 5.309 (solid), respectively.

B. Bag radius in finite nuclei

With the density dependence of the bag radius obtained from the modified QMC model, we are ready to evaluate the average bag radius in a finite nucleus, A , in the local density approximation:

$$\overline{R}_A \equiv \frac{\int d^3r R[\rho_A(r)] \rho_A(r)}{\int d^3r \rho_A(r)}, \quad (2.8)$$

where $\rho_A(r)$ is the density distribution of the nucleus A and $R[\rho_A(r)]$ denotes the bag radius at the density $\rho_A(r)$. Here we adopt the phenomenological fits in a form of the Woods-Saxon type function for the density distribution $\rho_A(r)$ [29]

$$\rho_A(r) = \frac{\overline{\rho}_A}{1 + \exp[(r - \mathcal{R}_A)/a]}. \quad (2.9)$$

Here the three parameters, $\overline{\rho}_A$, \mathcal{R}_A and a , are used to fit shapes of nuclei. Their values for various nuclei [29] are listed in Table I.

low and moderate densities and take $Z = Z_0$. Recently, Blunden and Miller [9] have considered a density dependent Z . However, it is found that for reasonable parameter ranges changing Z has little effect and tends to make the model worse.

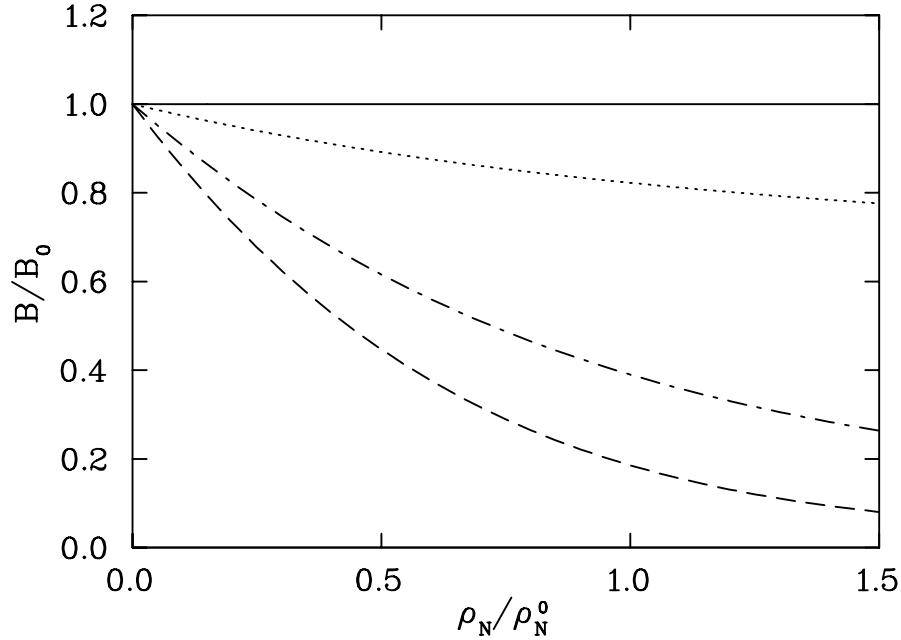


FIG. 2. Corresponding result for the ratio B/B_0 as a function of the medium density. The same parameters are used as in Fig. 1. The four curves correspond to $g_\sigma^q = 1.0$ (long-dashed), 2.0 (dot-dashed), 4.0 (dotted), and 5.309 (solid), respectively.

TABLE I. Parameters $\bar{\rho}_A$, \mathcal{R}_A , and a in Eq. (2.9) to fit the shapes of nuclei with $A = 12, 20, 27, 56, 63, 107, 118, 197$, and 208 (from Ref. [29]).

Nucleus	$\bar{\rho}_A$ (fm $^{-3}$)	\mathcal{R}_A (fm)	a (fm)
^{12}C	0.1708	2.240	0.500
^{20}Ne	0.1628	2.740	0.569
^{27}Al	0.1738	3.070	0.519
^{56}Fe	0.1760	3.980	0.569
^{63}Cu	0.1674	4.218	0.596
^{107}Ag	0.1566	5.299	0.523
^{118}Sn	0.1607	5.412	0.560
^{197}Au	0.1694	6.380	0.535
^{208}Pb	0.1600	6.624	0.549

Figure 3 shows the resulting ratio \bar{R}_A/R_0 from model-I Eq. (2.6) as a function of g_σ^q for different nuclei, with $\delta = 4$ and $R_0 = 0.6$ fm. Here the couplings g_σ^B and g_ω^q are adjusted to fit the nuclear matter binding energy. The case $g_\sigma^q = 0$ ($\delta = 4$) corresponds to QHD-I (but with density dependent bag radius) [12]. The reduction of B in this case is large ($B/B_0 \sim 10\%$). On the other hand, $g_\sigma^q \simeq 5.309$ gives the usual QMC model, where the bag constant is independent of density (i.e., $B/B_0 = 1$). When $g_\sigma^q > 5.309$, the in-medium bag constant increases instead of decreases relative to B_0 (i.e., $B/B_0 > 1$).

It can be seen from Fig. 3 that for small g_σ^q , \bar{R}_A changes significantly with respect to R_0 .

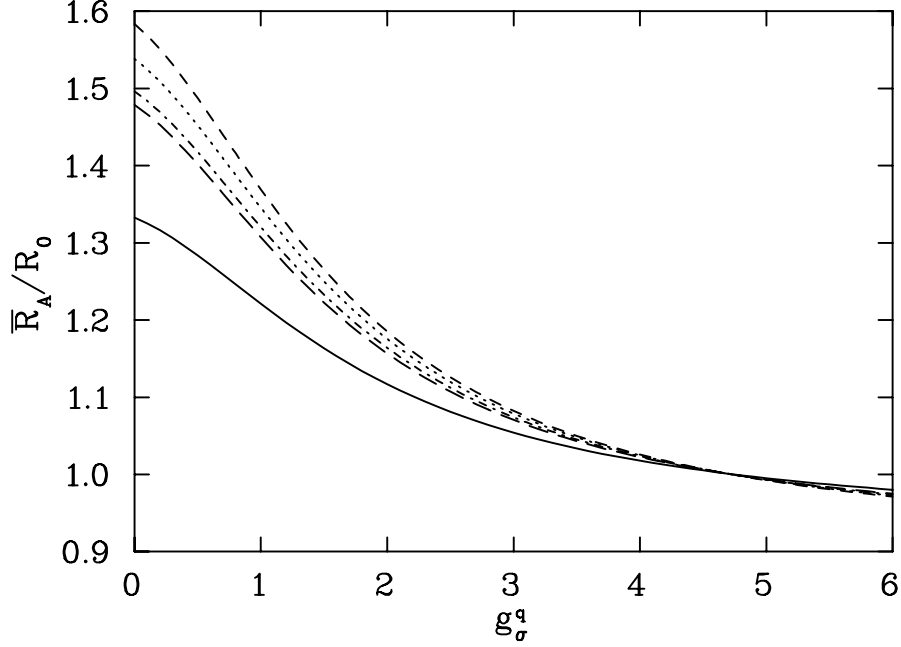


FIG. 3. Result for the ratio \bar{R}_A/R_0 as a function of g_σ , with $\delta = 4$ and $R_0 = 0.8$ fm. Here model-I Eq. (2.6) is adopted. The five curves correspond to $A = 12$ (solid), 56 (long-dashed), 118 (dot-dashed), 197 (short-dashed), and 208 (dotted), respectively.

As g_σ^q increases, the ratio \bar{R}_A/R_0 decreases quickly resulting from the increase of B/B_0 . The A dependence of \bar{R}_A/R_0 is strong for light nuclei. As A becomes large, the A dependence weakens and the ratio \bar{R}_A/R_0 appears to saturate. We also find that for a given g_σ^q , increasing δ leads to the increase of B/B_0 and hence the decrease of \bar{R}_A/R_0 , and for fixed g_σ and δ , the results are insensitive to the choice of R_0 .

The result from model-II Eq. (2.7) is illustrated in Fig. 4, where the ratio \bar{R}_A/R_0 as a function of κ is plotted with $R_0 = 0.6$ fm. Here the quark-meson couplings g_σ^q and g_ω^q are chosen to reproduce the nuclear matter binding energy. The case $\kappa = 0$ corresponds to the usual QMC model. For small κ values ($\kappa < 1.2$), the ratio \bar{R}_A/R_0 is close to unity. As κ gets larger, \bar{R}_A/R_0 increases rapidly. This is due to the decrease of B/B_0 with increasing κ . The ratio \bar{R}_A/R_0 in this case has similar A dependence and sensitivity to R_0 as in model-I.

We note that the results for \bar{R}_A/R_0 are largely controlled by the change of the bag constant in nuclear medium with respect to its free-space value. To illustrate this point, we have listed the values of \bar{R}_A/R_0 for different nuclei in Table II, with the ratio B/B_0 fixed at $B/B_0 = 40\%$ (at $\rho_N = \rho_N^0$). One can see that the results are fairly model independent and the sensitivity to R_0 is very small ($\sim 1\%$). When R_0 increases, the ratio \bar{R}_A/R_0 increases slightly. This variation with R_0 can be compensated by tuning down the ratio B/B_0 slightly. We have also tested the sensitivity of model-I results to the δ value and found that the results are insensitive to δ . (In the limit of $\delta \rightarrow \infty$, B/B_0 at $\rho_N = \rho_N^0$ is always larger than 40% for positive g_σ^q value).

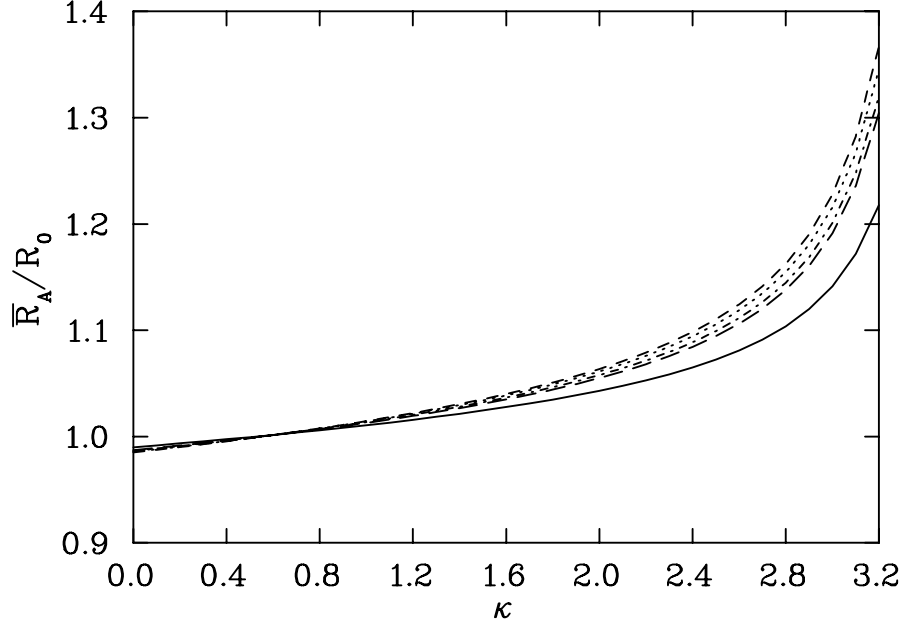


FIG. 4. Result for the ratio \bar{R}_A/R_0 as a function of κ , with $R_0 = 0.6$ fm. Here model-II Eq. (2.7) is adopted. The five curves correspond to $A = 12$ (solid), 56 (long-dashed), 118 (dot-dashed), 197 (short-dashed), and 208 (dotted), respectively.

TABLE II. Predictions for the ratio \bar{R}_A/R_0 , with B/B_0 fixed to $B/B_0 = 40\%$ (at $\rho_N = \rho_N^0$).

Nucleus	\bar{R}_A/R_0 (Model-I with $\delta = 4$)			\bar{R}_A/R_0 (Model-II)		
	$R_0 = 0.6$ fm	0.8 fm	1.0 fm	$R_0 = 0.6$ fm	0.8 fm	1.0 fm
^{12}C	1.113	1.119	1.121	1.115	1.121	1.123
^{20}Ne	1.113	1.118	1.121	1.115	1.121	1.123
^{27}Al	1.137	1.143	1.146	1.139	1.146	1.148
^{56}Fe	1.152	1.159	1.162	1.154	1.161	1.164
^{63}Cu	1.145	1.152	1.155	1.147	1.154	1.157
^{107}Ag	1.157	1.165	1.168	1.160	1.168	1.170
^{118}Sn	1.159	1.166	1.169	1.162	1.169	1.172
^{197}Au	1.179	1.188	1.191	1.182	1.190	1.194
^{208}Pb	1.170	1.178	1.181	1.173	1.181	1.184

III. IMPLICATION FOR THE EMC EFFECT IN DYNAMICAL RESCALING

In this section, we calculate the rescaling parameter from the change of the average bag radius in nuclei obtained in previous section and discuss its implications for the EMC effect in the dynamical rescaling approach. We refer the reader to Refs. [16–20] for further details and physical motivations of the approach.

The dynamical rescaling is based on that the confinement size for quarks in nuclei is larger than in free nucleons. This then leads to a rescaling relation [16–20]

$$F_2^A(x, Q^2) = F_2^N(x, \xi_A Q^2) , \quad (3.1)$$

which connects the structure function (per nucleon) in the nucleus A , $F_2^A(x, Q^2)$, to the nucleon structure function in free space, $F_2^N(x, Q^2)$, where x is the Bjorken variable and Q^2 is the probing momentum. Here the parameter $\xi_A(Q^2)$ is called rescaling parameter, which can be related to the ratio of the quark confinement scale in the nucleus A and that in the nucleon [19]

$$\xi_A(Q^2) = \left[\left(\frac{\bar{R}_A}{R_0} \right)^2 \right]^{\alpha_s(\mu^2)/\alpha_s(Q^2)} , \quad (3.2)$$

with

$$\alpha_s(\mu^2)/\alpha_s(Q^2) = \ln(Q^2/\Lambda_{\text{QCD}}^2)/\ln(\mu^2/\Lambda_{\text{QCD}}^2) , \quad (3.3)$$

where Λ_{QCD} is the QCD scale parameter. Here we follow Ref. [19] and take $\Lambda_{\text{QCD}} = 0.25$ GeV and $\mu^2 = 0.66$ GeV². In Eq. (3.2) we have identified \bar{R}_A and R_0 as the quark confinement sizes in the nucleus A and in the free nucleon, respectively. The relation Eq. (3.1) can also be generalized to any pair of nuclei, with ξ_A replaced by $\xi_{AA'}$ and R_0 replaced by $\bar{R}_{A'}$.

The rescaling relation Eq. (3.1) can be understood by considering the moments of the nuclear structure function defined by $M_n^A(Q^2) \equiv \int_0^A dx x^{n-2} F_2^A(x, Q^2)$. If one knows the moment $M_n^A(Q^2)$ at some initial value of Q^2 , say μ_A^2 which can be regarded as the low-momentum cut-off for radiative gluons, then it is calculable for all $Q^2 > \mu_A^2$. The idea of dynamical rescaling is that, since in perturbative QCD the target dependence resides in the nonperturbative matrix elements, the scale μ_A^2 may be target dependent and independent of n , such that $M_n^A(\mu_A^2) = M_n^N(\mu_N^2)$. Then, one finds for $Q^2 > \mu_A^2$, $M_n^A(Q^2) = M_n^N(\xi_A Q^2)$, which implies the relation given by Eq. (3.1). Further details and discussions can be found in Ref. [16–20].

The parameter $\xi_A(Q^2)$ is the most important input in the rescaling. Feeding the ratio \bar{R}_A/R_0 obtained in previous section into Eq. (3.2), one obtains the predictions of the modified QMC model for $\xi_A(Q^2)$. The resulting values at $Q^2 = 20$ GeV² are listed in Table III, where the values of \bar{R}_A/R_0 given in Table II (with $R_0 = 0.6$ fm) are used. The results of Ref. [18] are also given for comparison. One can see that the predictions for $\xi_A(Q^2)$ agree well with the results of Ref. [18]. (For larger R_0 , very similar results can be obtained with slightly smaller values of B/B_0 .) In particular, for iron the predicted $\xi_A \simeq 2$ and $\bar{R}_A/R_0 \simeq 1.15$ are essentially identical to those required to explain the experimental data [18]. The A dependence of $\xi_A(Q^2)$ is somewhat weaker than that found in Ref. [18]. This, however, has only small impact on the predictions for the EMC effect as the Q^2 dependence of the structure function is only logarithmic in the context of perturbative QCD.

It has been demonstrated in Refs. [16–20] that the values of rescaling parameter listed in the last column of Table III give predictions for the EMC effect in the medium x region which are in excellent agreement with the experiment data. Since our predictions for $\xi_A(Q^2)$ are very close to those values, we expect that the resulting predictions for the EMC effect will also be very similar. Here we shall not repeat the analysis. The interested readers can find the comparison between the predictions of the dynamical rescaling and the experimental

TABLE III. Predictions for the rescaling parameter $\xi_A(Q^2)$ at $Q^2 = 20 \text{ GeV}^2$. Here the values of \bar{R}_A/R_0 with $R_0 = 0.6 \text{ fm}$ listed in Table II have been used. The last column gives the results of Ref. [18] (using the Reid soft-core version of the correlation function).

Nucleus	$\xi(Q^2)$ (Model-I with $\delta = 4$)	$\xi(Q^2)$ (Model-II)	$\xi(Q^2)$ (Ref. [18])
^{12}C	1.69	1.70	1.60
^{20}Ne	1.69	1.70	1.60
^{27}Al	1.88	1.89	1.89
^{56}Fe	2.00	2.02	2.02
^{63}Cu	1.95	1.96	2.02
^{107}Ag	2.04	2.07	2.17
^{118}Sn	2.06	2.09	2.24
^{197}Au	2.24	2.27	2.46
^{208}Pb	2.16	2.18	2.37

data in Refs. [16–20]. Thus, when the bag constant drops significantly in nuclear matter, $B/B_0 \simeq 35 - 40\%$, the predictions of the modified QMC model for the change of average bag radius in nuclei relative the bag radius of an isolated nucleon can lead to satisfying explanation of the EMC effect in the medium x region.

IV. DISCUSSION

As pointed out in Refs. [11–13], a significant reduction of the bag constant also implies large potentials for the nucleon in nuclear matter. In particular, when $B/B_0 \simeq 35 - 40\%$ at $\rho_N = \rho_N^0$, we find [30]

$$M_N^*/M_N \sim 0.72, \quad U_v/M_N \sim 0.21, \quad (4.1)$$

where $U_v \equiv 3g_\omega^q \bar{\omega}$. Since the equivalent scalar and vector potentials appearing in the wave equation for a point-like nucleon are essentially $M_N^* - M_N$ and U_v [8,9], Eq. (4.1) shows large and canceling scalar and vector potentials for the nucleon in nuclear matter, which are comparable to those suggested by the relativistic nuclear phenomenology [14] and finite-density QCD sum rules [15].

Such a large reduction of the bag constant is not entirely unexpected. If one adopts the scaling ansatz advocated by Brown and Rho [31], the in-medium bag constant scales like [32], $B/B_0 \simeq \Phi^4$, where Φ denotes the universal scaling, $\Phi \simeq m_\rho^*/m_\rho \simeq f_\pi^*/f_\pi \cdots$, which is density dependent. Here, the “starred” quantities refer to the corresponding in-medium quantities. Taking the result for m_ρ^*/m_ρ from the most recent finite-density QCD sum-rule analysis [33], one finds $\Phi \simeq m_\rho^*/m_\rho \sim 0.78$ at the saturation density, which gives rise to $B/B_0 \simeq \Phi^4 \sim 0.36$. There are, however, some caveats concerning this estimate which have been discussed in detail in Ref. [12].

Moreover, the dropping bag constant also leads to a swelling nucleon in nuclear environment. This has important implications for various nuclear physics issues which have been discussed extensively in the literature [34–39]. In the modified QMC model, the nucleon

swelling is also reflected in the outstretched quark wave functions (see Ref. [12]). This is supported by the studies of finite-density QCD sum rules [40] and other studies of the modification of internal structure of the composite nucleon [41]. It was found in these studies that there is a sizable reduction for the nucleonic wave function at the origin in nuclear medium relative to that in free space, which is an indication of outstretched wave function and nucleon swelling.

Therefore, the reduction of the bag constant in nuclear medium may play important role in low- and medium-energy nuclear physics. In particular, this reduction effectively introduces a new source of attraction for the nucleon which needs to be compensated with additional vector strength. On the other hand, the dropping bag constant also predicts the increase of quark confinement scale in nuclei which leads to the reduction of the momentum carried by the valence quarks and hence the depletion of the structure function in the medium x region. It is satisfying to find the mutual consistency and connection between the large nucleon potentials and the EMC effect. Thus, the modified QMC model provides a simple and useful framework for describing nuclear phenomena, which incorporates the quark structure of the nucleon, yet respect the established relativistic nuclear phenomenology based on point-like nucleons and mesons.

While it is attributed to the overlapping effect between two nucleons in Refs. [16–20], the change of quark confinement scale in nuclei results from the dropping bag constant in nuclear medium in the modified QMC model. The fact that the two approach give very similar predictions may imply that they describe similar physics. Our view is that the decrease of the bag constant in nuclear medium (through the coupling to the scalar mean field) and the resulting change of confinement size in nuclei effectively parametrize the physics of the nucleon overlapping effect and/or other more complicated nuclear dynamics. In this sense, the modified QMC model can be reconciled with the traditional picture of a nucleus as a collection of bound nucleons and the traditional description of nuclear physics in terms of hadronic degrees of freedom.

We note that other effects such as nuclear binding and Fermi motion also contribute to the EMC effect in the medium x regime. These effects should be applied in addition to the predictions of the dynamical rescaling if one is to fit the observed data. The inclusion of these effects may alter the phenomenological success obtained from the dynamical rescaling alone. For example, it is found in Ref. [42] that the nuclear binding and Fermi motion in the conventional model of the nucleons account for about 20% of the EMC effect in the medium x region (see, however, Ref. [43]). Consequently, the change of quark confinement size in nuclei required to explain the data is somewhat smaller than that discussed in the present paper.

However, the authors of Ref. [44] have claimed that dynamical rescaling mimics binding effects in the conventional model and it was argued in Ref. [20] that the nuclear convolution models [45] and dynamical rescaling provide alternative not different explanations of the EMC effect. This is consistent with our view of regarding the reduction of the bag constant and change of confinement size in nuclei as simple parametrization of detailed nuclear dynamics. Clearly, further study is needed to clarify whether the dynamical rescaling and the conventional approach are really independent or they describe the same physics.

Finally, it has been emphasized previously [12] that the QMC model is only a simple extension of QHD, where the exchanging mesons are treated as classical fields in the mean-

field approximation. The explicit quark structures of the mesons should also be included and the physics beyond the mean-field approximation should be considered in a more consistent treatment. It is also known that both the MIT bag model and the QHD are not compatible with the chiral symmetry. To improve this situation, one may use a chiral version of the bag model and a relativistic hadronic model consistent with the chiral symmetry.

V. SUMMARY

In this paper, we have confronted the modified quark-meson coupling model developed previously with the EMC effect within the dynamical rescaling approach. We used a local density approximation to evaluate the average bag radius in nuclei and determined the rescaling parameter from the change of the average bag radius in nuclei relative to the radius of a free nucleon bag.

When the bag constant is reduced significantly in nuclear matter, $B/B_0 \simeq 35 - 40\%$ at the nuclear matter saturation density, the predicted values for the rescaling parameter are in good agreement with those required to explain the EMC effect in the medium x region. This result is largely independent of how the in-medium bag constant is modeled and is very stable against variations of various model parameters. Such a significant reduction of the bag constant also leads to large and canceling scalar and vector potentials for the nucleon in nuclear matter which are consistent with those suggested by the relativistic nuclear phenomenology and finite-density QCD sum rules.

Since the predictions of the modified QMC model for the change of the average bag radius (quark confinement size) in nuclei are very similar to those obtained from modeling the overlap between two nucleons, it seems plausible that the reduction of the bag constant (through the coupling of the bag constant to the scalar mean field) effectively reflects the physics of nucleon overlapping and/or other detailed and complicated nuclear dynamics.

To conclude, the modified QMC model provides a useful framework for describing nuclear phenomena, in which the decrease of the bag constant in nuclear environment plays an important role. We have seen that the model gives consistent predictions for large nucleon potentials in nuclear matter and the EMC effect. We look forward to further vindication of this model in addressing other nuclear physics problems.

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